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13. ABSTRACT

The problem of photographically recording aircraft strikes is considered from the standpoint of the photographic instrumentation required. Emphasis is placed on recording guided weapon strikes during air-to-air encounters. Currently used and available techniques are enumerated and their advantages and disadvantages are discussed. Recommendations are made for continuing lines of investigation aimed at determining by test, the true usefulness of two of the techniques reviewed which are not currently in use. The appendices give background technical data on resolution required for aircraft detection, and optical problems involved in implementing the recommended techniques. Optical data and samples are given for a new design of panoramic lens system which appears promising. Attention is directed to the possibility of using preliminary automatic film scanning techniques to reduce the total amount of film to be interpreted.

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NAVAL ORDNANCE LABORATORY
White Oak, Maryland

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STRIKE CAMERA SURVEY

The Strike Camera Survey was prepared by the Naval Ordnance Laboratory, White Oak in response to AIRTASK A3705391/292B/1F08-132 701, assigned by NAVAIRSYSCOM, AIR 5391.

The Laboratory was assigned responsibility to investigate current aircraft strike camera technology and to suggest areas in which cameras and strike recording techniques should be upgraded in order to keep apace of planned aircraft and air-to-air weapons development. As a result, several new or modified techniques have been proposed and their relative merits and shortcomings have been discussed.

The authors of this report wish to thank Mr. Carl W. Larson of the Applied Physics Department for his contribution in the preparation of the spot diagram and MTF analysis of the Scripto Lens, a component part of one of the more promising strike recording systems proposed by this report.

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Commander

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By direction

CONTENTS

ILLUSTRATIONS

TABLES

Section 1 - Introduction

A strike camera, as defined in this report, is an aircraft-mounted camera which is used to record tactical data from an air-to-air or air-to-ground strike mission. This data normally includes the following: Identification of the target against which the ordnance is delivered; aim point; tactics employed both by the target and by the delivery aircraft; ordnance effects; and damage or kill confirmation. Strike cameras are normally not used for battle-damage assessment or other types of strategic evaluation reconnaissance resulting from air-to-ground bombing operations against enemy targets.

The two main categories of weapons covered in this study--ballistic, line-of-sight weapons (such as machine-cannon and 2.75 and 5-inch rockets) and self-propelled, self-guided weapons (such as AIM-7 and AIM-9 missiles)--impose widely varying requirements on any strike camera system. Additionally, the logical extension of technical capabilities of weapons and aircraft through the 1970's time frame and the dual requirement of training and combat strike recording also add their own specialized requirements on any given system.

BACKGROUND OF THIS STUDY

The Strike Camera Study was prompted by one central fact: that current techniques in aircraft strike recording leave much to be desired in terms of reliability, completeness of coverage, and ability to identify the desired elements in the processed film. This is particularly critical in recording long-range air-to-air strikes with guided weapons. As weapon and aircraft maneuverability increases, the situation will obviously become worse. Therefore, this study was requested to examine the current problems and investigate the ways in which photo-optic technology and instrumentation could be used to provide solutions, both for current and near-future aircraft and weapons systems.

SCOPE OF THIS STUDY

As noted above, certain elements are excluded from this study: specifically, coverage of conventional bombing and bomb-damage assessment. The emphasis of this study is on the photo-optical equipment required to provide the required strike record. Primary importance is placed on air-to-air strikes but consideration is also given to air-to-ground strikes using guns, rockets and self-powered guided weapons. The photo-instrumentation techniques presently available for recording these strikes are discussed and their advantages and disadvantages are enumerated. In conclusion, two systems are looked at more

closely: a tracking-type system (a development of an existing but not widely used technique) and the full-sphere system (a theoretical system to which no references were found in the literature). The full-sphere system appears to be capable of providing many of the advantages and none of the disadvantages of currently used systems.

Section 2 - The Ideal Strike Camera System

An ideal strike camera system for a fighter or attack aircraft would provide the following characteristics:

1. It will provide photographs of sufficient quality to allow recognition and positive identification of the target.

2. It will provide accurate recording of the aim point at the time of weapon release. This is particularly true if the recording system is to be used in a training mission.

3. It will record either weapon impact, miss-distance or self-destruct. The distance between aim point and a miss, if it occurs, should be evident for miss-distance analysis.

4. It will provide a record of the enemy's evasive maneuvers between weapon launch and impact. This is an important source of data for development of our own air-to-air tactics.

5. It will provide virtually automatic operation before, during, and after the strike so that the pilot does not have to expend effort in monitoring, aiming, tracking, starting, or stopping the camera.

6. It will provide manual over-ride of any automatic function so that the pilot can, if necessary, record unusual or unanticipated strike situations such as an unusual evasive maneuver executed prior to weapon launch.

7. The total field of view, irrespective of how it is achieved, will encompass the total airspace around the aircraft and not be limited so that certain targets cannot be covered by the field of view of the system.

8. Focal length and depth of field should be such that smallest target can be recognized and identified* at a slant range of five to ten miles, atmospherics permitting. Additionally, the minimum range of sharp-focus would be no greater than the minimum enabling and arming distance for any weapon carried.

9. The total recording time will be sufficient to record complete delivery tactics for each round carried.

10. Exposure time will be fast enough to provide sharp images even at close range with high angular rates of turn.

* See Appendix A for amplification of these requirements.

TABLE 1 - POSSIBLE STRIKE CAMERA SYSTEMS; SUMMARY OF

System	Camera Type	Location	Ideal Size	Best Application	Imagery Characteristics
1.	Gunsight*	Mounted on gunsight	16mm	Guns, short-range air-to-ground rockets	Max. range for good image, one mile.
2.	Camera strike* (Independent) (1)	Aircraft-or pod-mounted	16mm 70mm	Medium-range self-powered rockets	Large image, longer range characteristics. Lower sampling rates on large film sizes.
3.	Panoramic* (2)	Aircraft - or pod-mounted	70mm 9"	Strike reconnaissance	Horizon-to-horizon. Large image area directly beneath aircraft, great distortion of perspective.
4.	Tracking	Not determined	16-70mm	Guided missiles, all-purpose large image system	Large image, best potential for long range coverage, no distortion, best potentiality for detailed missile tracking
5.	Pilot's field	Not determined	16-70mm	Close-up gun and rocket strikes, secondary use for guided missiles	Not optimum for long-range strikes. May produce best compromise between maximum coverage at minimum equipment space and cost.
6.	Active, passive tracking	Not determined	16-70mm	Guided missile, all-purpose large image system	Large image, tracks missile rather than target, may not provide best miss-distance data or target maneuvers
7.	Full Sphere	Not determined	16-70mm (multiple camera)	Simple air-to-air or air-to-ground 360° coverage	Small image limits utility, some distortion but provides full coverage of airspace. Ideal for analyzing tactics.

*Systems of these types are currently in use.

( ) - Bracketed numbers indicate references in Appendix E.

11. The camera system will have an adequate frame rate but it need not have excessively high frame rates if other parameters in the system are properly balanced.

12. In spite of other demands placed on the system, it will be reliable in operation.

13. It will be easily maintained and adaptable to reasonable conditions imposed by Fleet supply and logistic demands.

14. The total system will use each camera to its best advantage with no more cameras than are required to provide the necessary field of view. Although a complex system will doubtless require more space than a simple gun camera, it should be remembered that any authorized accessory equipment competes with all other equipment and ordnance for a finite volume of available space.

15. It should provide a good balance between cost and the amount of usable data provided.

No system which could be proposed and successfully developed can achieve all of these goals; therefore, any strike camera system which is feasible to develop must contain compromises and trade-offs. One of the goals of this report is to consider some of the trade-offs required by each type of system.

Section 3 - Techniques: Seven Distinct Approaches to the Strike Camera Problem

There are a number of technical approaches which can be used to solve the problem of providing adequate photographic coverage of an air-to-air or air-to-ground strike. Seven generalized systems are described in the following pages. These systems could, if desired, be combined with one another in any number of possible combinations. The systems therefore are considered theoretical inasmuch as they represent particular avenues of approach to the problem rather than a description of equipments which could be installed on a particular aircraft. The systems are summarized in Table 1.

SYSTEM 1: GUNSIGHT CAMERA

Although it has a number of limitations, the gunsight camera is the most informative strike recording system presently available. If the camera is properly integrated into the design of the gunsight, it can provide more information for less effort than any other currently used system.

ADVANTAGES.

1. The gunsight camera always provides the pilot's aim point for ballistic weapons and lock-on or release point for self-guided weapons.

2. The gunsight camera requires no attention from the pilot, performing its required function whenever a weapon is fired and providing a sufficient overrun to record hits from aircraft's machine gun/cannon or ballistic rocket fire.

3. If properly integrated into the overall aircraft/weapons system (as is the HUD - "heads-up-display" camera on the A7 aircraft), it can provide much information in addition to aim-point or release-point.

4. The basic gunsight camera technique is standard, well understood, and provided for in the Fleet logistic system. New equipment of the same principle, in general, requires less Fleet training than new systems.

5. The need for a special camera alignment procedure for boresighting the camera with the aircraft Armament Datum Line (ADL) is eliminated. The only effect of camera misalignment will be that the image of the gunsight reticle will not be in the center of the camera field.

DISADVANTAGES.

1. Space in the cockpit of fighter and attack aircraft is at a premium particularly around the gunsight. The ability to provide longer recording times and larger cameras which can give higher reliability and better exposure control is limited by the space available.

2. Selection of the proper focal-length lens for the gunsight camera cannot be made independent of other factors when the total gunsight reticle is included in the camera field (and particularly if HUD data is included), a short focal-length lens (one to two inches) is required. Air-to-air strikes with long-range guided missiles require longer focal lengths if any reasonable amount of detail is to be provided. These assumptions are based upon the use of 16mm film and become even more restricting if a larger format is to be used.

3. The gunsight camera can record only a small portion of the total airspace around the aircraft, typically from $\underline{+}2°$ to $\underline{+}8°$ from the longitudinal axis of the aircraft itself. Much can be happening in areas not covered by the gunsight camera. Self-guided weapons frequently leave the field-of-view of the gunsight camera almost immediately after launch, providing no photographic coverage of the

target at the time of weapon impact. This is a severe limitation inherent in the gun-camera design as presently employed.

4. Many gunsight cameras (that on the F-8 is one example) impose some restriction on the pilot's field-of-view, either through the gunsight reticle (by casting unanticipated reflections on the canopy) or by blocking the view of other instruments in the cockpit. This is patently undesirable but, given adequate integration of camera design with the other avionics system, is an avoidable side-effect. Present practice, however, places the requirements for a gunsight camera rather far downstream in the design evolution and so adequate camera design integration is seldom achieved.

5. Location of camera windows is frequently less than optimum for best camera operation. In some aircraft, the window has been located so that it is almost parallel to the optical axis of the gun camera. This can introduce unwanted glare, lack of image contrast, and general optical degradation.

SYSTEM 2: STRIKE CAMERA (INDEPENDENT)

A separate strike recording camera is similar to a gunsight camera system but is located at some point in the aircraft other than the gunsight. Advantages and disadvantages of this type of installation are as follows:

ADVANTAGES.

1. Maximum flexibility of space usage. This type of installation can be located where space is available, a distinct advantage in fighter and attack aircraft where much space has been pre-empted by other avionics and ordnance equipment.

2. A larger film capacity can be utilized.

3. Longer focal-length lenses can be employed for better coverage of strikes at longer ranges.

4. Larger film format can be used.

5. Lack of space restrictions can allow the use of multiple cameras or a larger, and therefore, possibly, more reliable and sophisticated camera system.

DISADVANTAGES.

1. The pilot's aim point is lost unless time-consuming and complicated boresighting procedures are used when the camera is installed in the aircraft. With most pod-mounted cameras, the ground and flying boresight axes are not the same due to airframe stresses in flight.

2. For more sophisticated weapons systems, a heads-up-display camera may still be required, or at least be desirable. In this case, inclusion of an additional strike camera complicates the equipment.

SYSTEM 3: PANORAMIC CAMERA

The panoramic camera(2) is a proven camera system design and has become the principal strike recording camera, particularly for bomb damage assessment. The camera lens scans the image area, laying down an image on the film in a sequential manner. This allows the camera to record an image area from horizon to horizon without the need for a wide angle lens while still maintaining a large image size. The field matches the flight path of the aircraft; and the scanning motion of the lens solves some of the problems of keeping the camera aimed at the target, particularly in delivery maneuvers.

ADVANTAGES. The image quality of the panoramic camera can be quite good. The scanning system combines a high-speed focal-plane shutter with a lens or prism which rotates or swings over a fixed arc. This combination produces an effective shutter speed of less than 1 ms. When used with long focal-length lenses (3 inches and up) together with a wide choice of film widths, the scanning system can give highly detailed studies covering fields up to 40° by 180°.

DISADVANTAGES.

1. A significant disadvantage of the scanning camera is the image distortion which is inherent in its design. The combination of the lens scanning motion and the motion of the aircraft over the ground produces a highly variable rate of motion between the image and the film. This results in a variable distortion over the picture format. Unfortunately, this distortion is variable both in value and direction and cannot be readily compensated. The distortion present in all scanning camera systems of this type is the product of three components: (a) the scanning motion of the camera lens, or V_s; (b) motion of the aircraft on which the camera is mounted, or V_c; and (c) target motion, or V_t. Each motion is a vector which can vary both in amplitude and direction. In general, only V_s can be determined accurately, leaving V_c and V_t as two unknowns in any equation.

The characteristic result is a picture in which both time and distance are variable in a random manner along the length of the picture but relatively constant across the width. Scale cannot be determined for measurement of miss distance, cratering, or any other precision measurement unless the subject itself can provide its own scale in the area and plane of interest.

A scanning camera used in a strike recording role would distort a close-in aircraft moving at a high rate of speed parallel to the direction of the camera scan in such a way that it would cover an abnormally large portion of the field on that particular frame. It would be effectively "lengthened" in the direction of movement. Conversely, if the target direction is opposite to the direction of scan, the image will appear shortened. Therefore, although the panoramic scanning camera can cover large portions of the airspace around the aircraft (a desirable characteristic for a strike camera), the inherent distortion discussed above makes it considerably less than ideal.

2. The panoramic design does not lend itself to small, compact packaging. For the aircraft whose prime mission is reconnaissance, this is no problem. But for purposes of this study, the added space requirements are critical.

3. The panoramic camera is a complex mechanism and requires a high standard of precision in manufacture if quality data is to be obtained. Cost of the system is therefore high.

4. The field of view of a panoramic scanning camera is not ideally oriented to record air-to-air encounters. This could be remedied by proper application of the original design, but currently used camera mountings do not lend themselves to this type of application.

SYSTEM 4: TRACKING CAMERA

The tracking camera is designed to track a target throughout the entire encounter. It has many advantages which make it ideal for strike recording, particularly for air-to-air guided missile encounters. To date, however, it has posed an equal number of disadvantages, many of which are difficult to resolve.

ADVANTAGES.

1. Long-focus lenses can be chosen with primary emphasis on image size rather than field coverage. (Wide-angle coverage is necessary only to compensate for a camera's lack of ability to track a target.) Long focal-length lenses can provide adequate image size even at the long distances encountered in air-to-air missile strikes.

2. With a properly designed tracking system, it is possible to cover virtually all of the airspace around an aircraft. This is a greater area of coverage than can be obtained by any other single-unit camera system.

3. The tracking camera itself is relatively simple if the tracking system sensors and drive mechanisms are ignored. This lends itself to sound optical design, fast film rate, large film format and capacity, and does not require compromise of design principles which can provide total overall quality and reliability.

4. It produces the maximum amount of usable data per foot of film. If the camera tracks the missile properly from time of launch to time of weapon impact or weapon self-destruct, plus a pre-set overrun, a high proportion of the film will have informational value. Additionally, the tracking system with a long focal-length lens is probably the only system which can effectively record modern weapon strikes at maximum range with a fairly high degree of reliability and predictability.

DISADVANTAGES. The disadvantages associated with the tracking camera system accrue mainly from the difficulty of providing a reliable tracking drive mechanism. Because adequate technologies have not yet been developed for smooth, automatic target tracking, a development of a

reliable strike camera based on tracking principles could be difficult, expensive, and time-consuming. Some of the technological problems associated with a tracking camera are listed below.

1. Reliability. Simple optical tracking systems such as those used in the past are all highly contrast-sensitive. A minimum level of optical contrast between the target and the background is necessary for the sensor to lock on to the target. If during tracking, the sensor scans past an object with higher optical contrast, the sensor may track and follow the false target rather than the true target. Conditions such as a highly reflective lake, a single cloud illuminated by strong sunlight against a darker sky, the sun itself, and friendly aircraft can all present false targets to the sensor.

2. Requires Monitoring. Because of the tendency to follow false targets, it becomes imperative to monitor the system to make sure that it is tracking the required target. This is a totally unacceptable condition to impose on a pilot (or even the R.I.O.*) under the other stresses of combat.

3. Mounting Problems. The problem of mounting a tracking camera on an aircraft in a position where it will have an unencumbered field of view is difficult to solve. It could be solved by proper integration of the camera design with the aircraft as early in the design phase as possible, a consideration which is true of any type of strike camera but is more essential to any camera which attempts to cover the desired 360-degree field of view around an aircraft.

4. Contrast Enhancement. As noted above, a critical element in the operation of an automatic tracking system is the contrast ratio between the target and the background. A minimum ratio is necessary for lock-on. Normally, this lock-on is initiated by manual means; then during strike maneuvers, automatic tracking begins. Under most combat conditions, the target image would be relatively fixed in the camera field of view. The background however will be changing and shifting wildly. This means that the contrast ratio is constantly shifting, ranging from relatively low to high. If the system is to operate automatically and reliably, some type of contrast enhancement of the selected target is required.

5. Automatic Tracking with Lost Target. In the event that the target is momentarily lost from view, the camera needs some method whereby it can scan to recapture the target. Predicted relative target course, bearing, and azimuth are theoretically available to the aircraft but are so mathematically complex that they can be predicted only by computer. If sufficient computer space were available, and a computer output could be used to drive the camera tracking system when the original target has been lost, the chances of the camera picking up an extraneous target can be substantially reduced.

*Radar Intercept Officer

6. Alternate Target Tracking. Barring a computerized lost-target scan, the only exception presently known is the helmet directed system whereby the camera is aimed in the direction where the pilot is looking. A tracking system based on this technique could offer attractive possibilities as a supplementary system but probably would not be suitable as a solution for the total air-to-air strike recording problem.

7. Interpretation and Scaling. A tracking-type camera has no inherent way to determine target position with respect to the aircraft, or to a vertical or ground reference. Because in only a small percentage of the frames will any ground reference be visible, and because the background changes by an unknown amount between each frame, co-relating actual measurements (distances, attitudes, rates of turn, etc.) in the finished footage is frequently impractical.

One possible solution to the problem is to use the Photo-Theodolite principle whereby each frame of film has an adjacent printout showing the direction of the lens axis of the camera with respect to some known point of reference such as the aircraft's ADL.* Here, for the theodolite printout to have any real meaning, it has to be further supplemented by a printout which references the ADL back to an earth-perpendicular reference point. To determine relative movement with respect to time, still another time-referenced printout is required to indicate the instant of shutter opening time. This last printout is necessary if speeds, turn rates, and maneuvering data are to be obtained. Obviously, printouts impinge upon usable film image area and the complexity of the mechanisms necessary to produce these printouts is significant in itself. Some of the inputs for the printouts could be obtained from existing on-board computers or navigational systems, thus reducing the overall complexity to some degree.

No attempt is made in this report to analyze existing fire control and navigational systems to determine electrical compatibility with a drive mechanism for a tracking-type camera. This is a separate field of study quite aside from photo-optics.

SYSTEM 5: PILOT'S FIELD-OF-VIEW

This sytem is based on the fact that a combat pilot has a marked tendency to follow the target by eye as long as it is in his field of view. The concept was set forth in a series of interviews conducted at NATC Patuxent River for this study. It is possible therefore to use the principle of visual tracking to provide the desired photographic record of a strike. Theoretically, this can be accomplished in two ways: (a) make the field of view of the camera correspond to the field of view from the aircraft cockpit; and (b) make the camera track in the same direction in which the pilot is looking. In case (a), the camera must have a fixed mounting and a relatively wide angle field of view. In case (b), a flexible mounting is required; (an electro-mechanical coupling between the pilot's head and the camera-pointing mechanism) but, as compensation for the extra complexity, a longer-focal-length lens could be used.

*Datum or reference line axis used for calibration of aircraft weapon systems.

ADVANTAGES.
1. The strike recording system is simplified by attempting something considerably easier than 360° total-airspace recording. This advantage is realized, however, only when the pilot physically maneuvers his aircraft so that he keeps the target in view during the entire strike.

2. No current aircraft has a particularly large field of view from the cockpit. While this is not necessarily good from the total aircraft design and the pilot's point-of-view, it does simplify the requirements on the strike recording system by eliminating the need for ultra-wide angle coverage or multiple camera installations.

3. When a head-tracking system is used (item (b) above), the relatively small angle-of-view available to the pilot simplifies the installation and location problems of the system.

4. Either type of pilot's field-of-view system can be built without pushing current and existing equipment and techniques to their ultimate state of the art. This is important when considering interim systems which can be used until more sophisticated systems are developed.

DISADVANTAGES. The Pilot's field-of-view system falls far short of many of the previously set criteria for an ideal strike system. Most important is the fact that in air-to-air combat the enemy will do all he can to ensure that he can be seen by the pilot as infrequently as possible. This is particularly true during the first few moments of air-to-air combat when the pilot may be the hunted rather than the hunter. Compensating for this limitation, however, is the higher possibility that the most important part of the strike, the closing of an air-intercept missile on the target, will probably be covered.

1. Detail. The Pilot's field-of-view system must rely heavily on short-focus lenses with their characteristic lack of detail on long-range missile strikes. This presents a paradox; the principal asset of the system, recording off-axis events around the aircraft (such as detailing a missile strike with rapidly maneuvering targets for ten to twenty seconds), becomes its prinicpal shortcoming. Short-focus lenses are at their best in recording action close to the aircraft, but so is the simple gun camera in use at the present time, although its total field coverage is extremely limited when compared to the pilot's field-of-view concept.

2. Mechanization. If a longer-focus lens is to be used, then the pointing system becomes necessary. A long lens moved and pointed by the pilot's head could possibly record long-range encounters with more detail but they become expensive and complex because of the mechanism needed to couple the pilot's head to a camera-pointing drive system. Given the determination to build such a mechanism however, a field-of-view camera driven by the pilot's head would offer some advantages.

SYSTEM 6: ACTIVE-PASSIVE MISSILE TRACKING CAMERA

Probably the most effective solution to the tracking problem is to provide an active beacon on each weapon. The tracking camera would then follow the beacon, a technologically easier task than attempting to follow the target by optical contrast or other means. The beacon could be actuated at the moment of firing and would provide a continuous signal link with the aircraft on which the camera tracking system could home in.

The homing beacon radiation wavelength could be chosen to provide a maximum signal output over a line-of-sight distance with minimum of equipment and power-supply weight. The frequency which is selected could be used to provide a continuous link with the launch aircraft, thus permiting the continuous tracking of the missile through clouds, haze, and other conditions which might cause loss of visual contact.

ADVANTAGES.

1. Reliability. An active-passive system offers a greater reliability than any type of optical-contrast tracking system (System (4)). It would not require monitoring by the pilot and would be a distinct step in the direction of the much-desired "fully automatic" system.

2. 360° Coverage. Depending upon mounting, an active-passive camera system could cover the entire airspace around the aircraft just as adequately as the complex optical-contrast tracking camera described previously.

3. Detail. A real advantage of this system is its ability to record good detail over a wide range of distances. By the use of variable focal-length lenses (the "zoom" lens), wide-angle coverage could be used during the first portion of the missile strike while the missile is still at close range with progressively longer focal lengths being used later. The zooming action could be entirely automatic, controlled as a function of time from launch.

4. Lost-target Tracking. With visible or near infra-red tracking systems, a complex lost-target search system is required if the missile or target flies into a cloud or is obscured for any other reason. Because of the continuous radio link, a true "lost target" is improbable.

DISADVANTAGES.

1. Missile Complexity. Any system which requires additions or modifications to an existing weapon is obviously going to have a battle in order to win approval. The additional cost for the beacon for each missile is significant and must be justified by several procurement desks. (Only guided missiles could justify the addition of the beacon equipment; their cost per round is such that the additional expense of the beacon could be justified by the amount of data which could be received).

2. Logistics. A beacon placed in each missile places a logistic burden on assembly, maintenance, and manufacturing facilities. Although not significant in itself, it is nevertheless an additional component adding its weight and complexity to the total missile design. Obviously missile checkout procedures would have to be more complex, the beacon would have to be small enough to fit into the existing missile electronics package, a modification to the missile launch circuitry of the aircraft might be required, and manufacturing changes in the missile would have to be effected.

3. Space Availability. This problem is always present but is more critical where a complex system is concerned. There appears to be no solution other than to put another black box into the already crowded electronics bay. The need for this equipment seems more likely than with any other system, including the complex optical-contrast system which does not require a specific control link between the target and the aircraft.

4. Missile-versus-Target Tracking. In this system, the missile rather than the target is tracked. In many cases, this is of academic interest only; but, when the target aircraft successfully evades the missile, we fail to record the most important aspect of the encounter: i.e., What tactics did the enemy use to successfully counter our weapon?

5. Data Link. The problem of jeopardizing a weapon by enemy countermeasures based on the presence of an active beacon would have to be considered. The problem is minimized by a number of factors: (a) the beacon frequency is presumably unknown to the enemy pilot; (b) it is not present until the missile is launched; or immediately thereafter; (c) the frequency could be rotated very easily to prevent its being used as a countermeasure; and (d) there are other phenomena associated with a missile strike (infra-red, etc.) which could be used more easily by the enemy. No attempt has been made to propose a specific type of data link, this being a separate study unto itself. A high-frequency, omni-directional beacon coordinated with directional receiving antennae on the aircraft should provide an adequate link through a wide range of maneuvers. With an active-passive system however, the control link from the missile to the aircraft remains uninterrupted, thus providing continuous tracking even when the missile is not visible from the aircraft.

6. Mechanization. Although quite complex, the technology required for an active-passive system is not nearly as demanding as that required for an automatic optical tracking system. As a consequence, a workable active-passive system could be developed and placed into service at much less expense than a comparable full tracking system.

7. Training. Because the system is virtually fully automatic, no additional training burden would be placed on the pilots. This is most significant when compared to the optical contrast system (System (4)) where at least some form of monitoring (therefore engendering training) would appear necessary.

8. Cost. When compared to systems delivering comparable results, it is believed that an active-passive tracking system would cost less both to develop and to manufacture than any other tracking type, even taking into account the expendable cost of the beacons required for the missiles.

9. Referencing. The active-passive system shares with the optical contrast tracking system (System (4)) the common problem of referencing the film footage to a fixed point in space. The same solutions are applicable.

SYSTEM 7: FULL-SPHERE CAMERA

The full-sphere camera is any wide-angle recording system which provides continuous coverage approaching 4π steradians of solid angle around the aircraft.* It is the only system which can simply and easily record everything which transpires during a strike mission. It would be relatively easy to develop a feasibility study prototype for this system using existing technologies in spite of the obstacles that remain for a complete solution of the problem.

ADVANTAGES.

1. This is the only system which can provide simultaneous (as opposed to scanning-type) coverage of the entire airspace around the aircraft.

2. Tactics Record. Continuous full-sphere recording appears to be the best method of obtaining a complete record of enemy aircraft tactics as well as documenting the tactics of our own aircraft during an actual engagement or during a training exercise. Because full-sphere recording will, by definition, show the sun-earth-horizon relationships, aircraft attitudes can be easily identified and interpreted.

* Solid angles around an object point are measured in terms of the area of space covered on an imaginary sphere of given radius. This solid angle unit is called the steradian. (S.R.) An area of any shape whatever which measures one square foot on the surface of a sphere of one-foot radius has a solid angle of one steradian. The size of the sphere and the unit of measurement are immaterial as long as they are consistent. Since the total area of a sphere is $4\pi R^2$, in a sphere of unit radius, there are 4π or 12.57 steradians total solid angle. It is convenient to rate the effectiveness of the proposed full-sphere camera in terms of the percent of the total solid angle it can cover. Thus:

$$\% = \frac{\text{Total area of coverage X 100}}{(\text{radius})^2 \text{ X } 12.57} \quad \text{or} \quad \frac{\text{Total S.R. X 100}}{12.57}$$

3. Air-to-Air Recording. Strike recording of air-to-air encounters is rapidly approaching the point-of-no-return with modern guided weapons. The time will be soon at hand when the only practical way to record a strike will be (a) to keep the camera always pointed at the missile; (b) keep the camera pre-aimed at the point where the target and missile will intersect; or (c) continuously cover the entire airspace. With all of its disadvantages (discussed later), full-sphere recording is still the most direct and non-mechanized approach to the problem.

4. Multiple-Target Coverage. A new concept in air-to-air combat is the ability to make multiple launches of independently targetable missiles (the PHOENIX weapon system may eventually have this capability). Full-sphere recording is the only practical system whereby two or more targets can be covered simultaneously. Even though such a system is considerably in the future, the application should not be overlooked.

5. Coverage of Missing Aircraft. The full-sphere system is the only system which automatically records the activities of companion aircraft in the near vicinity engaged in the same strike. Because of this feature, a considerable degree of additional coverage will be provided on any multiple aircraft operation against a common target. Because this data comes from different perspective viewpoints, it can, in many cases, contribute additional information not obtainable in any other manner, rather than just back-up coverage. And in case of mechanical failure in the recorder or loss of the strike aircraft, a record of operation of the missing aircraft MAY be obtained. With all other systems, records of the missing aircraft occurs only through chance. With a full-sphere recorder with sufficient film capacity to record everything during a strike operation, some record of all missing aircraft within recording range will probably be recorded in any multiple aircraft operation. Such information could be crucial in ascertaining the cause of loss and in devising remedies. In addition, its usefulness in training is obvious.

DISADVANTAGES.

1. Optical Problems. The biggest single drawback to any camera attempting to cover the total airspace around the aircraft is that of optics. At present there is no way (and little hope that there ever will be) in which this field can be covered by a single camera and lens system. A single camera and lens system has many advantages in size, weight, and simplicity and is extremely desirable from a logistics and operational viewpoint.

2. Mounting. As soon as a strike camera field approaches the 4π S.R. coverage, camera mounting becomes of great importance. The simplest, practical system (two fish-eye 180° coverage cameras mounted back-to-back or side-by-side and pointed in opposite directions) will have a portion of its coverage lost by vignetting by the supporting structure. The obvious solution is early incorporation into the aircraft design so two units could be mounted symmetrically, pointed

opposite and with little axial separation as possible. Two immediately obvious points for mounting are at the wing-tips or at the top of the vertical stabilizer and the bottom of the fuselage, directly underneath. For minimum vignetting, the optical axes of the two units should be parallel, even though displaced. With this system, the only loss of coverage from the full sphere would be a flat disc with a thickness equal to the axial separation of the two lenses. Percentage-wise, this is small, even for two wing-tip cameras with 30-50 feet of axial separation. These two points (or their equivalent positions, depending on aircraft contour) provide the minimum amount of field vignetting.

Section 4 - Summary Description of Major Strike Recording Problems

The major problem areas in the field of strike recording which have been identified in this report are summarized below:

1. The need for greater detail in any photographic record. Most photographic systems provide the poorest quality output in that area which is of greatest interest to the air-to-air intelligence officer: the long-range missile strike with the enemy using evasive maneuvers, or the short-range machine cannon attack in which the field of view is so limited as to provide sketchy data on all but a small portion of the encounter.

2. The need for exposure control of the strike camera. While not called out as a specific problem on any one system, the lack of a reliable automatic exposure control for the strike camera is a problem which applies equally to all systems. Much film footage can be lost due to gross over-exposure or under-exposure due to rapidly changing positions of the sun. A truly reliable system will require that this problem be significantly overcome.

3. The need for reliability. This is true of any system but is more true of the sophisticated systems which, because of their nature, must be more complex.

4. The limited space available on any strike aircraft. Adequate space will have to be planned during the design phase of most aircraft if some of the more complex systems are to be installed. Space considerations also encompasses the mounting problem for full-sphere or tracking type cameras.

5. Limited area coverage. Present systems photograph only selected areas of small area coverage. This is completely unsatisfactory for missile strike recording.

6. Limitations of atmospherics on strike recording. Under best conditions, a camera could be used out to a range of five to six miles, but frequently atmospheric haze limits its range severely. This problem is one with which we must live but it can be relieved somewhat by automatic filtration on the camera to extend its ability

to penetrate haze and by carefully optimizing film characteristics and processing. However, a real breakthrough is required in this area.

7. The need for multiple systems to fully record the strike. No present system used singly can record all aspects of every strike. Multiple systems will have to be used if this objective is to be realized. The important question is how many?

8. The increasing importance of coverage of "hidden" areas. These areas were once of minimal concern in offensive strike recording (directly aft, beneath, to-the-side) but are now of significant importance. This increases the area of desired coverage manyfold, as these areas will become increasingly critical as guided missiles become more important. Full-sphere coverage would seem to be the only solution.

9. Multiple targets present problems which cannot be solved with any reasonable or practical system except one which provides full-sphere coverage.

The authors are not implying that these are the only problems present but they are major and will become even more important as missile ranges and relative speeds increase.

Section 5 - Conclusions and Recommendations

Statistics and reports from Southeast Asia have emphasized the importance of air-to-air combat within visual contact range, even though missiles have a much longer theoretical range. Stated simply, there are either standing rules against firing at an unidentified target (a radar blip, for example) or reluctance of pilots to fire at any aircraft without positive visual identification. It follows therefore that most air-to-air strikes are made in an environment where they can be recorded photographically. As a result of this survey, it would seem advisable to upgrade the techniques of strike photography.

We can assume for purposes of this report that the goal is to provide an all-purpose, general use, strike-recording camera. This camera should provide a significant improvement over existing equipments both in its primary mission of providing strike coverage and in a secondary role as a training aid for combat techniques. For this goal, the following recommendations are made:

1. Establish a systematic effort, even if conducted at a minimum level, to prove or disprove the utility of the full-sphere strike camera system. The simple back-to-back, two-unit 180° system should be examined critically. As an interim camera or special-purpose recorder, it could be conveniently bread-boarded using existing techniques and tested for effectiveness during air exercises. This simplified full-sphere camera should be most useful for recording detailed target analysis or miss-distance.

We should explore the possibilities of scaling up some of the 180° controlled-distortion lenses to obtain larger images. Estimates obtained from designers(3) of such lenses indicate a possibility of extending their focal lengths to three or more inches axially. See Appendix B for details of the problems in this area.

2. Continue the search for and utilization of other elements in the implementation of a full-sphere recording system. As an example, two samples(4) of non-spherical optics have been examined which appear to have special promise in the development of such a system. Design data on the non-spherical lens indicates that while the ultimate resolution may not be diffraction-limited, it is still high enough to offer significant advantages. The logical way to evaluate this type of lens would be by production of a prototype lens and camera system for bench and field evaluation under simulated strike conditions. Results obtained with an early experimental model of this lens are impressive. This may well amount to a major advance in lens design philosophy and would seem to represent a most desirable path for future exploration. (See Appendices C and D for design principles and 150° photos.) Manufacturing problems would also have to be evaluated simultaneously as this lens represents a radical departure from conventional and traditional techniques, and neither should the problems of mounting a full-sphere system be neglected.

3. As the range of weapons increase, the obvious demand for a long-range recorder becomes more urgent. The atmospherics which limit photography and TV systems and the poor resolution which limits radar would appear to be inescapable boundary conditions. A special purpose, long-range recorder would appear to be the answer.

A two-pronged approach could be developed: a narrow-angle active-passive photographic strike system (described as system 6) designed for maximum atmospheric penetration would be a possible short-term solution. Simplicity, small size, and reliability should be the top goals. Long-term requirements might be met through the design of a non-photographic system to minimize the atmospheric and range limitations inherent in optical systems. At this point, however, techniques which are theoretically sound appear to be sophisticated, elaborate, and based on long-range research which would have to be balanced against the benefits to be gained. However, the simple, reliable, wide field photographic recorder would appear to be an important tool for many years to come.

4. All of the recording methods described in this report have the inevitable disadvantage, to a greater or lesser extent, of bringing back much film which does not have usable data. All of this film must be evaluated however; and the visual monitoring of thousands of feet of film, only a small portion of which is important, is time consuming and inefficient. There is an immediate need to develop an automatic scanning technique whereby strike recording film can be automatically viewed at a high rate of speed and those portions with usable or significant data earmarked for evaluation by conventional photo-interpretation techniques.

The need for such equipment is obvious when we consider a three-camera, indexing, full-sphere recorder. The output of such a system may carry useful data on only one or two frames in every six, with other systems producing an even higher ratio between usable and useless film footage. Automatic target recognition techniques (possibly applied during processing or at some subsequent step) could cue the film so that the interpretation projector or printer would display only those frames with pertinent information for initial review. The total film footage would still be available for detailed examination, however.

An automatic scanning system could eliminate much of the drudge work which would otherwise fall on the photo-interpretation specialist but would not jeopardize the value of the total information package obtained during the strike. It has an intrinsic value far past the strike problem considered here and should be pursued through prototype, field test, and field evaluation, unless it becomes apparent that expense or reliability makes it impractical. The minimum camera sampling rate should also be determined as a part of the evaluation.

APPENDIX A

RESOLUTION REQUIRED FOR LONG RANGE DETECTION AND RECOGNITION

Figure A-1 has been prepared to serve as a starting point for quickly determining the minimum focal length or the maximum range at which a given focal length system with a performance characteristic of 50 lines/mm can detect or recognize a fighter type aircraft (such as the A-4) with a maximum dimension of approximately 30 feet. The figures are not based on tests and should be used with caution. They are convenient for comparing the relative probable performance of similar systems under indentical conditions.

As a general rule of thumb, three levels of quality are generally recognized in classifying photographic imagery for quality. They are detection, recognition and identification.

We will use the term detection to imply the ability to determine that, at a given point on a photo, a foreign object exists which is probably an aircraft. It is not possible at this level to always say, with complete assurance, that the object is an aircraft.

Recognition implies the ability not only to determine that the object is an aircraft, but whether friendly or enemy, and what type ...an A-4 fighter or B-52 bomber?

Identification implies a still higher order of quality in the image. No attempt will be made to deal with the problem at the identification level since it is dependent on many variables and may represent a relatively unneeded advance in strike photography quality. Our primary interest is two-fold: first, detecting the presence of a significant aircraft and second, recognizing the type of aircraft and whether it is friend or foe. These two levels of picture quality are considered to be adequate for this purpose when used for comparing the relative merits of two similar systems looking at the same target under the same conditions. No assertion is made that these are absolute standards assuring positive detection or recognition at the ranges stated for aircraft in general.

The detection levels assigned are based on the assumption of a total system performance (including atmospherics, subject-background contrast ratio and other degrading factors) of 50 lines per millimeter. If five or more resolution elements cover the image area, we can then detect it as an aircraft.

We can now consider what the resolution is in terms of distance at the object plane. The detection level we use implies a resolution

of approximately five feet at the object per element of film resolution, each element consisting of one line and one space of equal width. The critical parameters of object contrast and atmospherics must be considered as being included when the subject is considered resolved.

From Figure A-1 it is quickly seen that with a four-inch lens our predicted range for detection will be approximately 32,000 feet or slightly under six miles, and recognition at about half that range. A thirty-foot object at 30,000 feet subtends an arc of 0.057° or approximately one miliradian. The maximum resolution of the human eye is normally given as one minute of arc, or 0.3 mils.

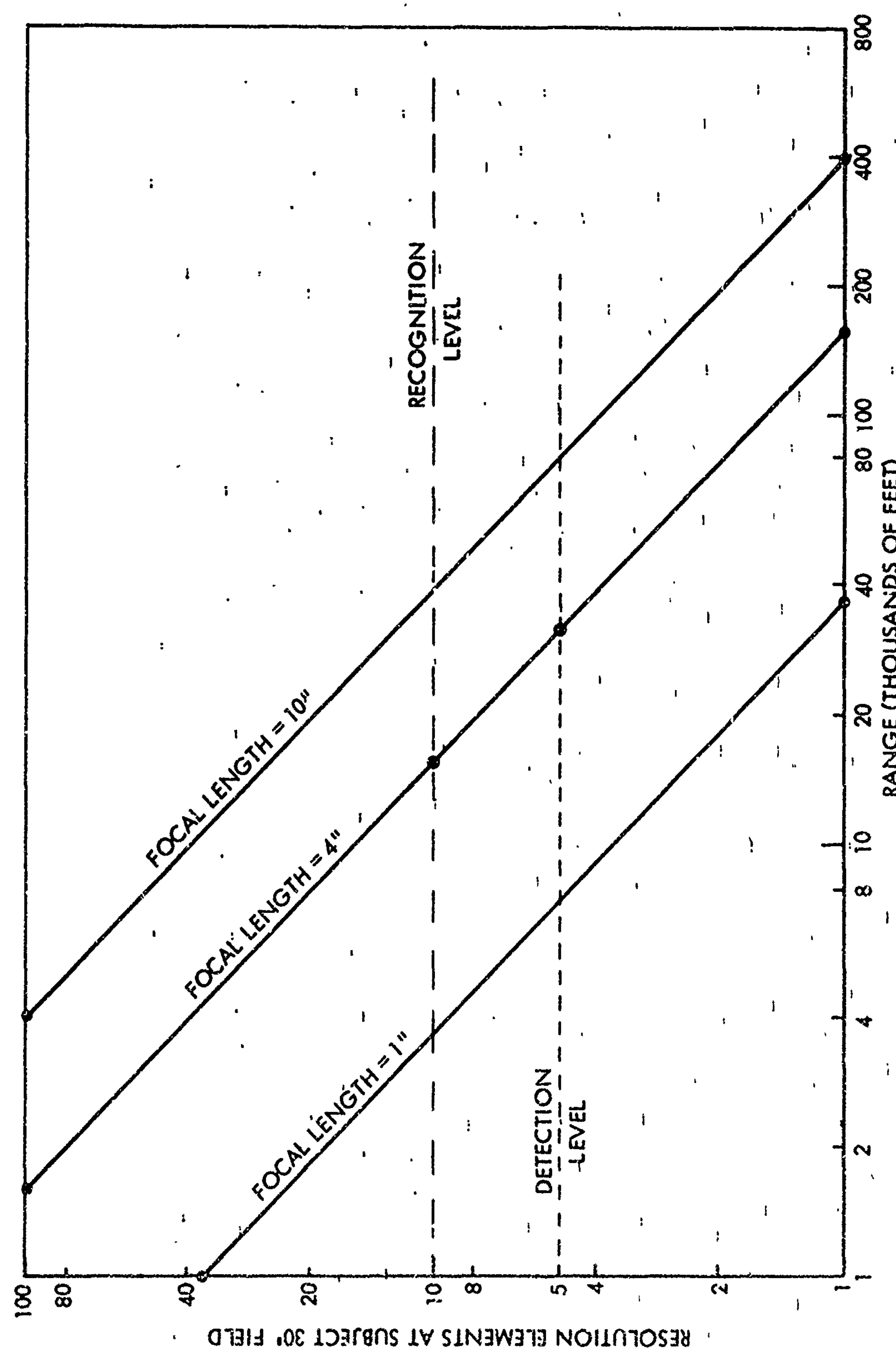


FIG. A-1 MAX. DETECTION & RECOGNITION RANGES FOR OBJECT ≈ 30' FOR VARIOUS OPTICAL SYSTEMS
(BASED ON A-4 AIRCRAFT - 50 LINE/MM SYSTEM)

APPENDIX B

EXTREME WIDE-ANGLE LENS PRINCIPLES

INTRODUCTION

The problems and advantages of 4π steradian (full-sphere) coverage for a strike recording system have been discussed previously in the body of this report. By way of summary, three basic approaches to full-sphere recording have been suggested:

(1) Use two extreme wide-angle lenses back-to-back, each with a 180° field of view; (2) Use several distortion-free lenses of narrower fields-of-view and multiply the number of units required to provide the full 4π steradian coverage; or (3) Use some type of indexing system which will monitor separate sectors of the sky sequentially but which will, over a desired time interval, provide the necessary coverage.

Given the task of designing a full-sphere system, it is readily apparent that there are serious shortcomings in any one of these three approaches. The simplest and most readily implemented approach, that described in (1), is handicapped by inherent optical characteristics for which no satisfactory solution is in sight. These limitations are discussed in detail in this appendix. Approach (2) is merely an attempt to circumvent these shortcomings by adding additional mechanical processes. Approach (3) and its possibilities are discussed in Appendix D.

An examination of approach (1) reveals the inherent optical limitation of current wide-angle lenses, almost all of which utilize spherical lens elements and image on plane surfaces. To fully understand these limitations, it is necessary to examine the distortion, illumination, and focal length characteristics common to ultra wide-angle spherical lenses with plane image surfaces.

DISTORTION CHARACTERISTICS

DEFINITION OF DISTORTION IN PHOTOGRAPHIC LENSES. It is convenient to explain distortion in photographic lenses from the standpoint of the chief ray(5) which enters the lens system.

By definition, the entrance pupil of an optical system is the image of the aperture which limits the angular subtense of the cone of rays from the object point to the lens. In general in photographic systems, the aperture is a physically adjustable element (diaphram) of variable area. The lens images this variable area window through which light rays enter the system. The chief ray is defined as that ray from any

object point being considered that passes exactly through the center of the entrance pupil. All optical systems are reversible. For every object point there will be a corresponding image point; for every entrance pupil, an exit pupil; for every chief ray in the object space, there will be a corresponding chief ray in the image space. We are concerned with the relative angles which the object and image chief rays make with respect to the optical axis, for object points that are not on the optical axis. Denote by θ the angle which the object chief ray, for a selected object point P_1, makes with the optical axis. The corresponding angle for the image chief ray will be θ'. If the following relationship holds true for all angles within the image area that is used then the lens is said to be distortionless:

$$\frac{\tan\theta'}{\tan\theta} = \text{constant.}$$

SIGNIFICANCE OF DISTORTION. Figure B-1 depicts a pin-hole "lens" which is inherently distortionless.

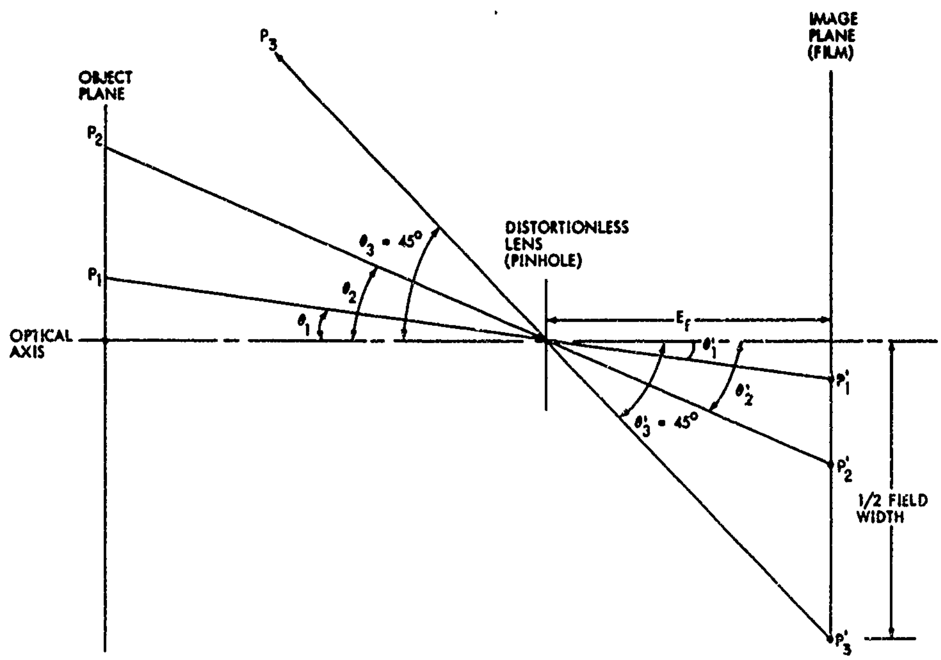


FIGURE B-1

It is obvious that as the angular field of view of the lens is increased, the focal length must be decreased or the film size increased. In the limit, to get a lens with a 180° field of view would require a zero focal length and an infinite film size. In practice, this is circumvented by the introduction of controlled distortion. This is true for a flat image surface.

Distortion, when present in any lens, can take two forms, pincushion or barrel. Going back to the fundamental relationship, if $\tan\theta'/\tan\theta$

decreases in value as θ increases in value we have barrel distortion. In this condition, as the object point moves away from the axis, the image point is receding from the axis at a less rapid angular rate. For an object θ degrees off axis, the image will be $\theta' \underline{+} \theta_{d'}$ degrees off axis, where $\theta_{d'}$ is the angular distortion component for the object angle θ. With barrel distortion $\theta_{d'}$ will always be negative.

In the case of the real optical system rather than a pin hole "lens" this constant relationship between the tangents of the angles of the object and image chief rays is not inherent. Many elements in the design of the lens effect the angular relationship and thus determine whether or not a lens is distortionless. The lens designer can opt for a design such that as θ increases,

$$\frac{\text{Tan } \theta'}{\text{Tan } \theta} \neq \text{ constant and decreases in value, thus}$$

purposely introducing barrel distortion. Referring back to Figure B-1 it is seen that it should be possible to pick up object points that are 90° or more from the optical axis and compress their corresponding image points into angles considerably less than 90° from the axis in this manner. This is the solution used in extreme wide-angle lenses designed for field coverage of $\underline{+}60°$ up through $\underline{+}90°$ or more degrees. Many off-the-shelf objectives of this type are available for immediate use.

SIGNIFICANCE OF ILLUMINATION IN WIDE-ANGLE LENSES

A second factor that must be considered in any extreme wide-angle system is the angle at which the light rays strike the recording film. It can be shown that the relative luminance of any image point off the axis of a distortionless lens system (as compared to the same image point on axis) is proportional to the fourth power of the cosine of the angle from the axis. For a lens with a $\underline{+}60°$ field of view, this means that the illumination at the edge of the image field will be $(\text{Cos}^4 \cdot 60) = (0.5)^4 = 0.0625$ or about 6 percent of that on the axis. This reduction in the luminance of the image will cause severe underexposure of all except the central part of the image under normal conditions.

This fall-off in illumination is a fundamental consequence of the laws governing image formation and is not the result of manufacturing faults or design. Many attempts have been made to correct the Cos^4 fall-off. The introduction of barrel distortion into lens design results in variable magnification across the field and provides some improvement in the illumination problem.

FOCAL LENGTH CHARACTERISTICS

Examination of the size of the image of a lens into which controlled distortion (or any distortion) has been introduced reveals the major shortcoming of the extreme wide-angle system.

The term "effective focal length" (E_f) which is usually used in reference to photographic objectives means that the complete

photographic objective produces an image of the same size as that produced by an aberrationless, thin lens of focal length F equal to E_f. For the thin lens, the focal length F is equal to the distance from the lens surface to the image plane when the object is at infinity. The thin lens has a thickness of zero so F is the same regardless of which surface of the lens it is measured from. For a thick lens or system E_f is measured from a defined "principal point" for design purposes but can be determined by measuring the size of the image the lens produces or measuring the relationship between object size/object distance ratio and the corresponding image ratio. Using the conventional notation where F equals focal length; S = distance from front principal point to object; S' = distance from rear principal point to image; h = object size; h' = image size; θ = angle between optical axis and object point; θ' = angle between optical axis and image point for the same object point; F = focal length we can then use the following relations to express the focal length of a system.

$$1/S' + 1/S = 1/F \text{ or } F = \frac{SS'}{S + S'}$$

$$M = \theta'/\theta = h'/h = S'/S$$

For extreme wide-angle lenses with controlled distortion it is apparent that M is no longer constant, but varies as h or θ varies; and since, for a given object and image distance, this implies that E_f varies with the angular position of the object in the lens field; and, likewise, that the image size will vary with its position in the image field. The normally stated focal length value will be true only for relatively small areas immediately surrounding the optical axis. As we approach the edge of the image field, the barrel distortion causes the image size and "apparent focal length" to decrease rapidly. Thus, for the extreme wide-angle lens, the image area at the edges of the field of view may be largely useless because even though the resolution may be very good, the image size may be too small for effective analysis.

To summarize then: For wide-angle lenses with field extended to 180° by the introduction of barrel distortion we have been limited to relatively short focal lengths, normally much less than one inch; the focal length varies with the location of the object in the image field, being much shorter at the edge of the field than in the center. For wide angle lenses that are distortionless, the maximum field angle is limited to some value not much more than ±50°, the illumination falls off very rapidly for image areas that are any appreciable angle off the optical axis, and the focal length is in general also limited to relatively short values.

Some lens designers have indicated their belief that it may be possible to scale up the central focal length of 180° lenses with controlled distortion. This might provide central focal lengths approaching three inches. Two such systems operating back-to-back would be the most simple and direct approach to securing a prototype for

assessing the value of the full-sphere system but the basic handicap of the controlled-distortion lens (reduced image size at the edge of the field) remains and is a major defect. A second handicap is the large size which would be normal to such a system. The only method we have found of avoiding this defect (without going to the panoramic type camera and trading one type of image defect for another one equally serious) is by use of the principles involved in the non-spherical lens system described in the following Appendices C and D.

APPENDIX C

ALTERNATIVES TO SPHERICAL ELEMENT WIDE-ANGLE LENSES

Conventional wide-angle photographic objectives are restricted by the limitations inherent in their design and manufacture. These limitations, as discussed in Appendix B, are applicable whenever an optical system is based on spherical lens surfaces and plane image surfaces. There are sound physical reasons for using spherical systems. They are by far the easiest shape to grind and polish to high precision with simple equipment. They are inherently self-generating. Modern manufacturing methods have, however, made spherical surfaces less mandatory than at any previous time in optical history.

One approach to the problem of wide-angle coverage appeared early in the history of photographic lenses. This was the Goerz Hypergon extreme wide-angle lens (6) which increased angular coverage by the use of symmetrical construction consisting of two almost hemispherical, meniscus elements concentrically located around a central stop. Other examples can be found in the literature of semi-concentric and concentric designs constructed for the purpose of achieving wide field coverage. All suffer from the illumination problem discussed in Appendix B.

An alternate approach is to make use of the concentric principle and design for a spherical image surface. This method has received application in such instruments as the Schmidt Camera.

From the optical point of view, a principle which appears to have great promise and which to our knowledge has not been previously described in the literature is the system of non-spherical, concentric lenses with cylindrical image surfaces which are the subjects of U. S. Patents 3251266 and 3361512 issued to David L. Fuller. The author of this report has had the opportunity of examining a prototype model of this lens (3-inch focus F.4.5.) mounted in a 70mm camera which provides a field coverage of 40° x 146°*; a plus-X negative taken with camera over Washington, D. C. was furnished for study and is reproduced in this report together with ray-trace data on a later version of the lens design. The camera and other information

*In the following discussion the terminology "horizontal refers to distances or points along the 146° dimension of the image and "vertical" to distances across the narrow dimension or 40° side.

were provided by the manufacturer and developer of the Fuller lens, Scripto, Inc., of Atlanta, Georgia. The sample of work done with this lens together with our evaluation of its optical performance are contained in Appendix D. This section is concerned with the unique principles of this lens and how it differs from conventional spherical lenses.

This lens makes use of the following design features:

a. The basic lens elements are segments of rings bounded by cylindrical or toroidal surfaces rather than the circular discs bounded by segments of spheres used in conventional lenses.

b. The lens is designed to produce a cylindrical image surface.

c. Oversimplifying, the basic design may be considered analogous to two separate cylindrical systems with quite different properties, with the system's axes oriented at right angles to each other(7). The use of crossed cylinders to provide conventional imagery has been experienced by anyone who has viewed a "Cinemascope" movie, as far as basic principles are concerned.

d. The focal length of the two systems are made equal although their aberration characteristics are quite different.

e. The locus of the image surfaces of each of the two systems are made to coincide.

f. The entrance pupil of the complete system is rectangular rather than round. The slit aperture stop which defines the width of the entrance pupil (controlling the illumination in the vertical meridian) is located at the center of the system and functions in the normal manner. A separate aperture stop controls the height of the entrance pupil (and the illumination in the horizontal meridian). It is also concentric, but of quite large radius. By this means, the entrance pupil area is made a function of the angle between the object point and axis of symmetry which would correspond to the optical axis in a conventional spherical system. In the horizontal meridian, the entrance pupil area can be left constant or made to increase or decrease with the field angle and the normal $\cos^4$ fall-off of illumination in a distortionless lens can be completely compensated in the horizontal meridian.

g. The basic design hinges on the concentric stop and radial elements to achieve wide angular coverage in one meridian. The radial system is designed specifically for the needs in this meridian. The "axial" system which images the vertical meridian follows conventional spherical lens design, in general.

h. The lens is designed distortionless in the horizontal direction, since there is no need to introduce controlled distortion to increase angular coverage when a radial image surface is used.

Qualitatively the concept is relatively simple and makes use of fundamental design principles which are common in most lens design problems. The combination of principles is what seems to be unique. By analogy, the system may be looked at as two independent optical systems each of which produces a meridional image with the meridians at right angles to each other. The field of view in the horizontal meridian is panoramic and covers up to ±75°. The vertical meridian is more conventional and covers up to ±25°.

The benefits which have apparently been gained by this design are impressive.

a. The stringent relationship between total field of view and focal length are now much more independent. In the unit examined, three-inch focal length was combined with 146° field of view (Figure C-3). This can be scaled up to 24-inches focal length without loss of field of view, according to the designer. Because of the concentric construction, picture size, image size and focal length are directly proportional. Maximum resolution will be less with longer focal lengths, as usual.

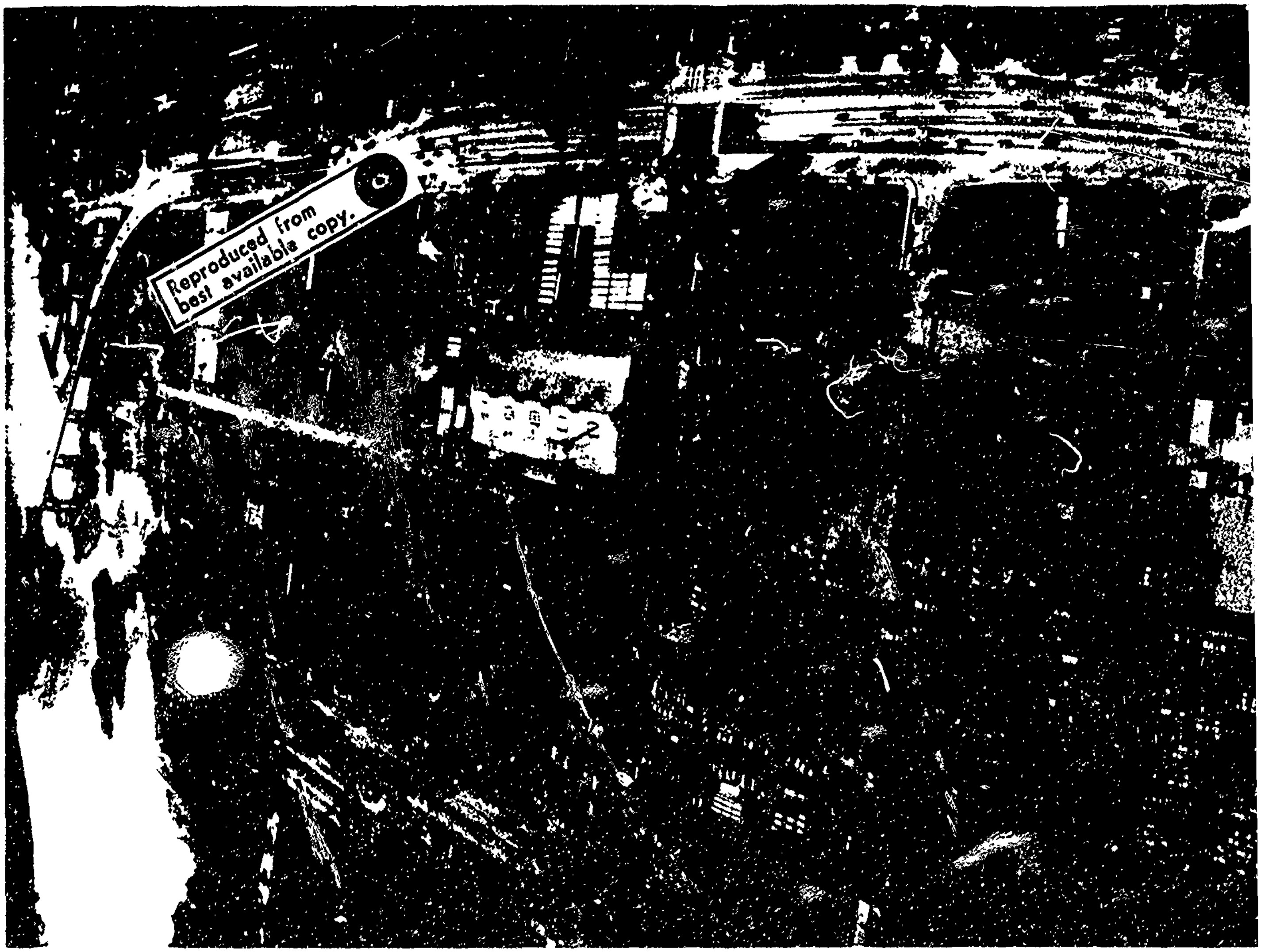
b. Curving the image plane and separating the stop into two parts has eliminated most of the illumination fall-off at the edges of the field to an even greater extent than is possible with conventional design. The major fall-off in illumination is now across the narrow side of the field with illumination being practically uniform from end to end of the full 146°.

c. Resolution and contrast appear to be essentially constant along the full 146° length of the field. This is not contradictory to fact since we are looking at the resolution of an annular system (in this direction) and basically a large percentage of all rays forming the image are axial rays. Resolution along the 40° or vertical meridian appears to degrade in the normal manner across the narrow dimension of the image.

d. The lens is essentially distortionless. The focal length is the same for all parts of the image area. In this respect, it is far superior to system 3, Table 1 and to most conventional wide-angle systems with fields of view exceeding 100°. It possesses the additional advantage that, since the system is fixed and involves no scanning, any small amounts of higher order distortion that might be found on more detailed analysis could be rectified by printing or projecting through a similar system.

e. Separating the lens elements into two systems provides the lens designer with a powerful new tool. Two major benefits seem at first glance to be available. The separation of the stop into two separate elements allows the annular element to be shaped to compensate partially, completely or overcompensate for the Cos^4 fall-off along the long dimension of the film, resulting in even illumination over the full 150°. The slight fall-off across the 40° dimension is not troublesome, and with black and white film it is hardly noticeable.

The second benefit comes from the fact that the focal surface of the axial system is determined by the design of the axial elements and that of the radial system by the front element. This separation of the two meridians into two separate systems allows for a separate correction of each system for its contribution to radial and tangential astigmatism. This appears to allow astigmatism to be highly corrected. In addition the curvature of the radial and tangential image surfaces can now be separately controlled, giving an additional degree of freedom in design.



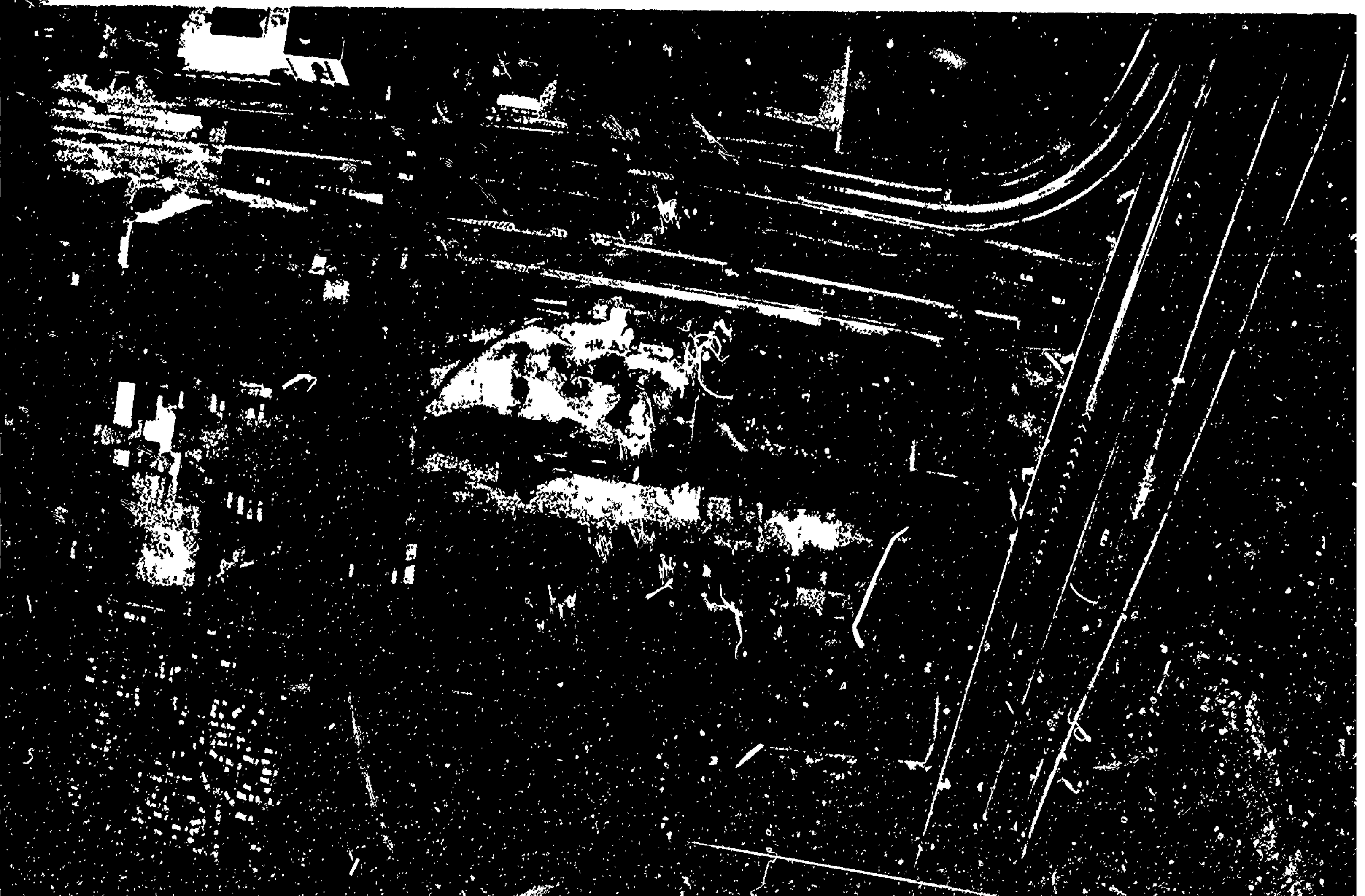


FIG. D-1 2.25 X BLOW-UP OF 40° x 146
NON-SPHERICAL CONCENTRI

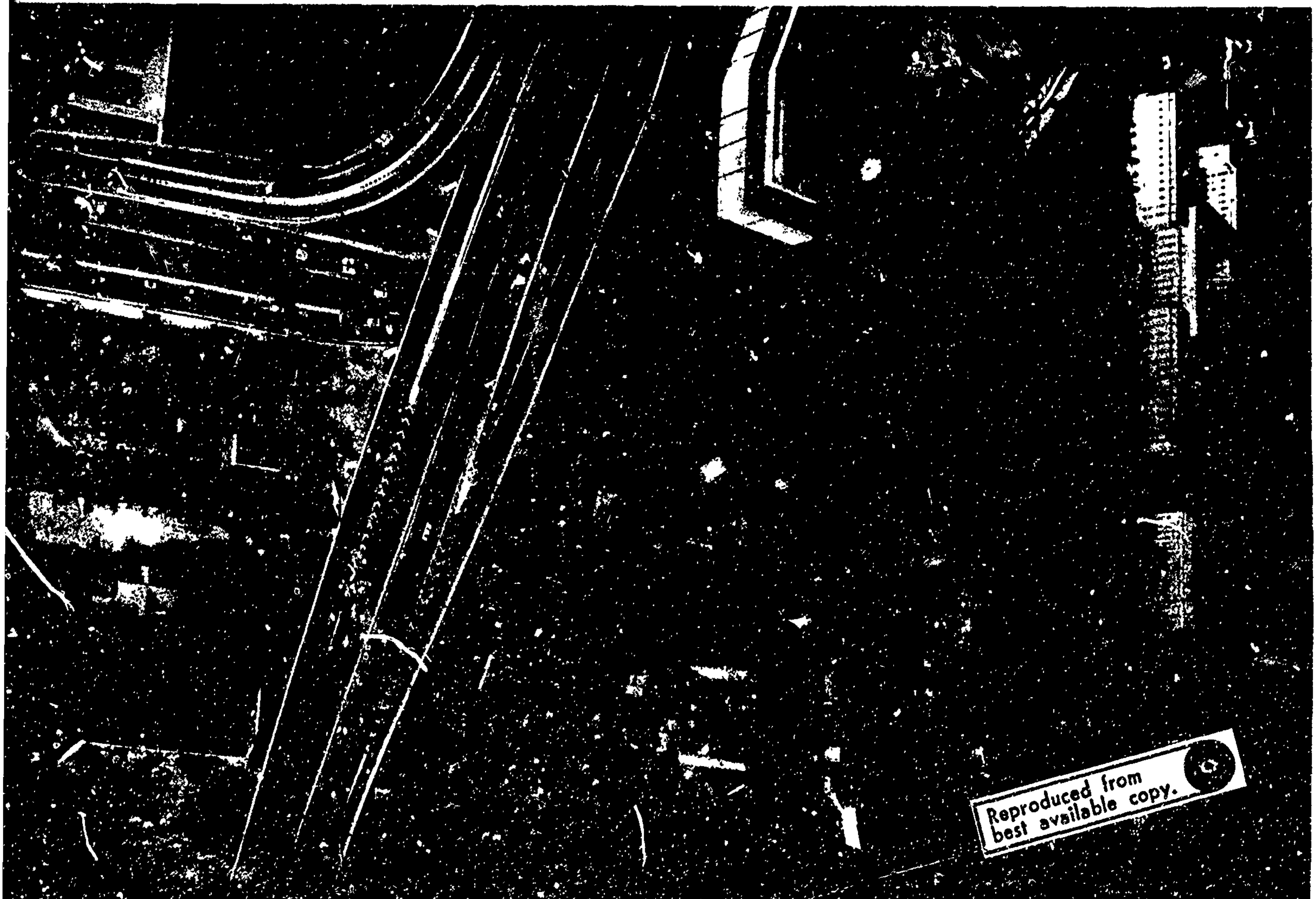


FIG. D-1 2.25 X BLOW-UP OF 40° x 146° PHOTO TAKEN BY FULLER DESIGNED NON-SPHERICAL CONCENTRIC LENS

FIG. D2 15X ENLARGEMENT FROM CENTER OF NEGATIVE. TAKEN WITH 75MM FULLER NON-SPHERICAL LENS. Altitude 1100 Ft

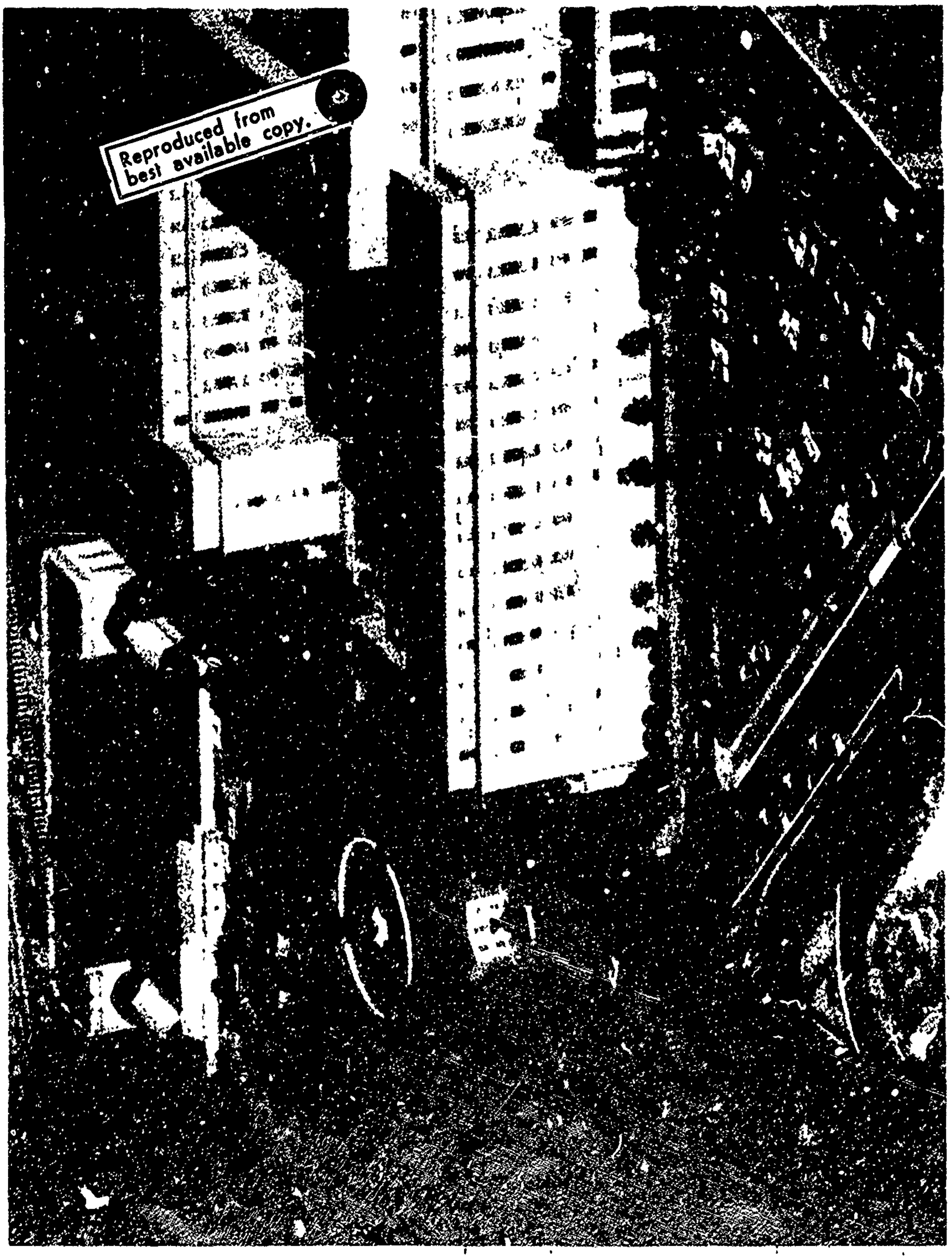


FIG. D3 15X ENLARGEMENT FROM EXTREME CORNER OF 75MM NEGATIVE. TAKEN WITH 75MM FOCAL FULLER NON-SPHERICAL LENS. ALTITUDE: 1100 FT (VERTICAL) SLANT RANGE TO SUBJECT: 4300 FT

APPENDIX D

NON-SPHERICAL LENS RESULTS AND POTENTIALITIES

Figure D-1 is a typical wide-angle photograph obtained with a prototype, all glass non-spherical Fuller lens with an oil-immersed shutter mechanism, as developed by Scripto, Inc. of Atlanta, Georgia. Technical details of this system are as follows:

Lens: 75mm Focal Length, F.4.5.
Field of View: 40° by 146°
Negative size: 70mm. Picture area: 2.18" by 7.64"
Altitude: approximately 1100 ft
Film: Kodak Plus-X Recon
Exposure: 1/1000 second
Shutter: rotary, between-the-lens, oil immersed
Film plans: cylindrical curved, 75mm radius
Printing system: negative flat, conventional spherical lens imaging plane-to-plane
Magnification: Figure D-1: 2.6X Figures D-2 and 3: 15X (Ratio: Reproduced size/negative size.)

FOREWARD TO DISCUSSION

In discussing the non-spherical lens the following facts should be kept in mind.

1. Conventional aerial photographs are made from negatives which are held in flat planes when they are exposed, when they are contact printed, and when they are projected or enlarged. Figure D-1 was made from a negative that was shaped as a cylinder when it was exposed and as a flat plane when it was contact printed and enlarged. Hence distortion is introduced both during contact printing and enlarging by the exigencies of the printing process used. A distortionless contact print cannot be produced from negatives made with the Fuller lens. Distortionless enlargements are easily made by merely projecting the images with the same type of lens that made them, the same as is done with conventional photographs.

2. Even though the printing process we were forced to use introduced distortion into the reproduction (due to lack of a non-spherical enlarging lens), it should be noted that the distortion produced is not extreme, unpleasant to the eye, or of the type that makes interpretation extremely difficult. The distortion is present only in the horizontal direction in the reproduction. It could be compensated for by using a variable-magnification grid overlay on the reproduction or contact print to scale off measurements. This is not true of the panoramic type of camera (System number three).

3. The enlargements for Figures D-1 and D-2 and D-3 were made from an early prototype, the first all-glass lens constructed from this design. Current design data shows a substantial advance in performance (predicted) as compared to the example shown here.

DISCUSSION

RESOLUTION. The resolution in the sample is probably most readily apparent by examination of Figures D-2 and D-3 which are sections of fifteen time enlargements of the original negative, taken at the center of the frame for Figure D-2 and near the extreme corner for Figure D-3. For the altitude of the aircraft during exposure, the difference in slant range to the two objects is in the approximate ratio of 1110 to 4380 feet. This also should be allowed for in considering the relative resolutions because of the obvious atmospherics at the time the shot was made. Note that there is no problem in identifying automobiles at the range of approximately 4000 feet. It was estimated that the effective ground resolution on the example would allow for the detection of objects about one half the size of those that could be detected with the naked eye at the same range and conditions. Subjectively we would rate the sample print as about average in resolution but slightly softer than that obtainable from a top quality recon lens of the same focal length and print size.

ILLUMINATION. The general evenness in illumination over the full field can best be judged from Figure D-1. This is not the result of dodging in printing, although some dodging was done. Large area density readings in the original negative are approximately as follows:

a. Center of negative: 0.9 to 1.0
b. Sides of negative at center of long side: 0.6 to 0.8
c. Corners of negative: 0.7 to 0.9
d. Ends of negative at center of short side: 0.8 to 0.9

In making these readings areas were picked near each of the indicated points which indicated, as near as could be subjectively judged, points of equal subject reflectance and illuminance. This is obviously not exact. The overall appearance of the negative does suggest quite uniform exposure with no apparent density fall-off.

DISTORTION. The picture can be considered distortion-free or distorted, depending on the point of view. In terms of how the eye sees the subject, from a fixed point of view, the reproduction is semi-distortion-free. Because of the large angle of view, it would be necessary for the eye to scan from horizon to horizon to see the same subject area. The familiar convergence of parallel lines as they approach the horizon would occur visually, as it does on the reproduction, but not to an identical degree. The observer can estimate range by the relative amount of convergence at a given point along the picture.

From the conventional photographic viewpoint, the reproduction is distorted. Conventionally, the reproduction is said to be

distortion-free if a rectangular subject plane parallel to the film plane of the camera is reproduced as a rectangle. In this example such a subject would be reproduced as a barrel and the lens would be said to exhibit conventional barrel distortion.

The above conventional interpretation assumes that the contact print from a negative and a projection print from the same negative will exhibit the same relative geometry in the reproduction, changing only the overall magnification of the image. This cannot be true for a negative that was non-planar when taken and contact-printed in planar geometry.

The present reproduction was taken with a non-planar lens system and reproduced with a planar system. It was shaped as a cylinder during exposure and as a plane during reproduction. Hence we have distorted reproduction. If the negative is re-shaped to the same radius it had when it was made and projected through a similar type of lens system to that used in making it, the reproduction will be distortionless: the rectangle in the original subject that was parallel to the image plane in the camera will be a rectangle in the reproduction. The convergence of parallel lines as they approach the horizon will disappear in the reproduction as it does with conventional spherical image reproductions. We have here a powerful tool for photogrammetry, since once the enlarger is adjusted to match the camera tilt the projected image will match a ground survey point-by-point over the full picture area. The non-spherical system is completely equal in every respect to the spherical distortionless system, as far as distortion is concerned. In addition it has the potentiality for a two to three-time field angle increase in one direction, plus regaining uniformity of illumination in this direction.

RAY TRACE DATA

While we were unable to make a detailed ray trace of the actual lens design used for taking the sample print Figure D-1, we were provided the output data of a ray trace schedule on an improved version of the Fuller lens by Scripto. The data was based on the following lens:

Focal length: 3.0 inches
Aperture: F2.8
Object Distance: Infinity
Program used: GOALS
Other lens parameters: Not furnished to NOL (this is presently proprietary information).

The output of the goals trace, based on wavelengths of 486, 586, and 656 millimicrons, was provided in the form from which the spot diagram of Figure D-4 was made. These diagrams are for an axial object location at infinity and the dotted circle is the diffraction limit radius for an F2.8 aperture. Figures D-5 and D-6 represent the calculated values of the modulation transfer functions for an object location on the axis and at the edge of the field, respectively. Based on this data we estimate that the limiting angular resolution of this design would be approximately 15 seconds of arc. This

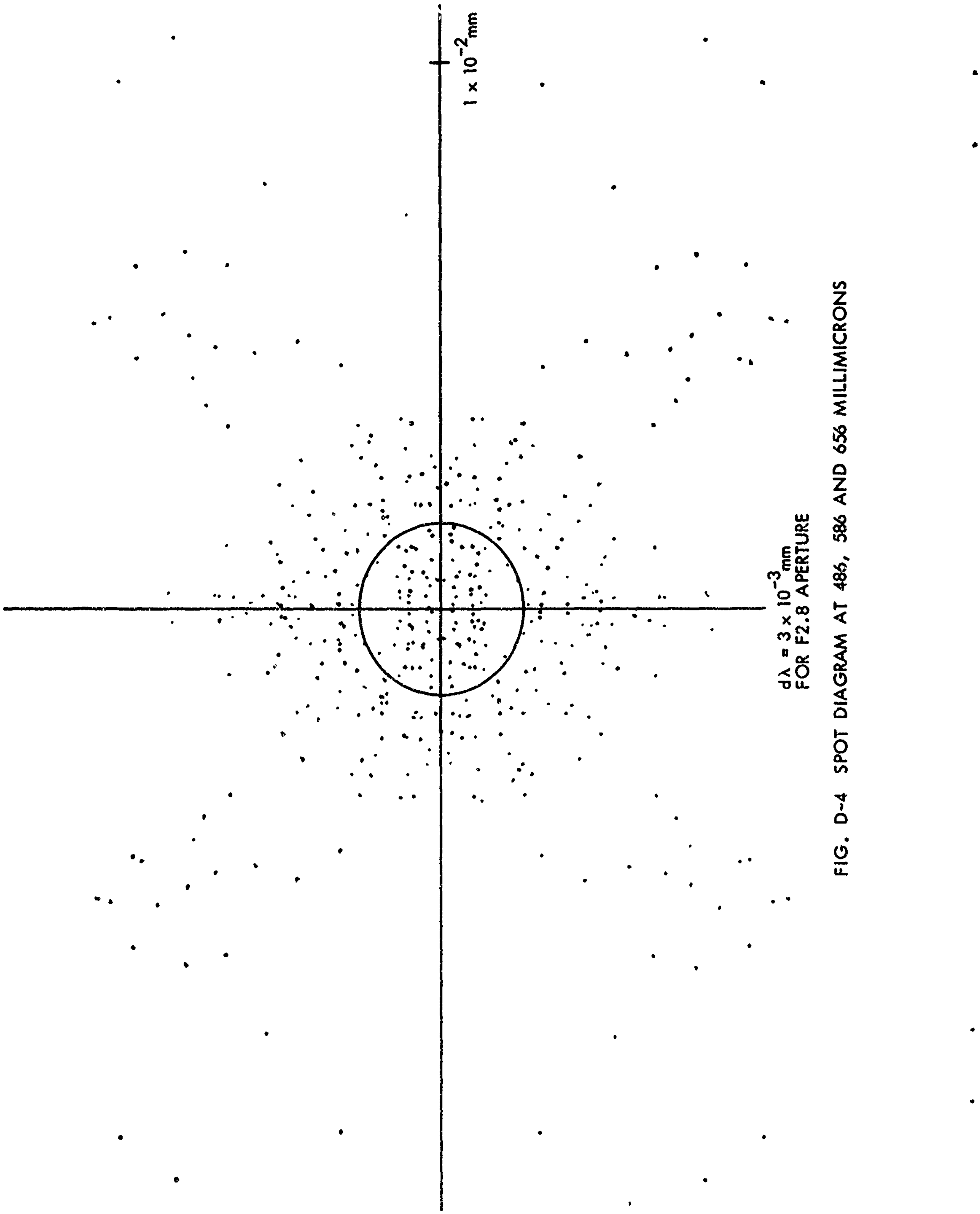


FIG. D-4 SPOT DIAGRAM AT 486, 586 AND 656 MILLIMICRONS

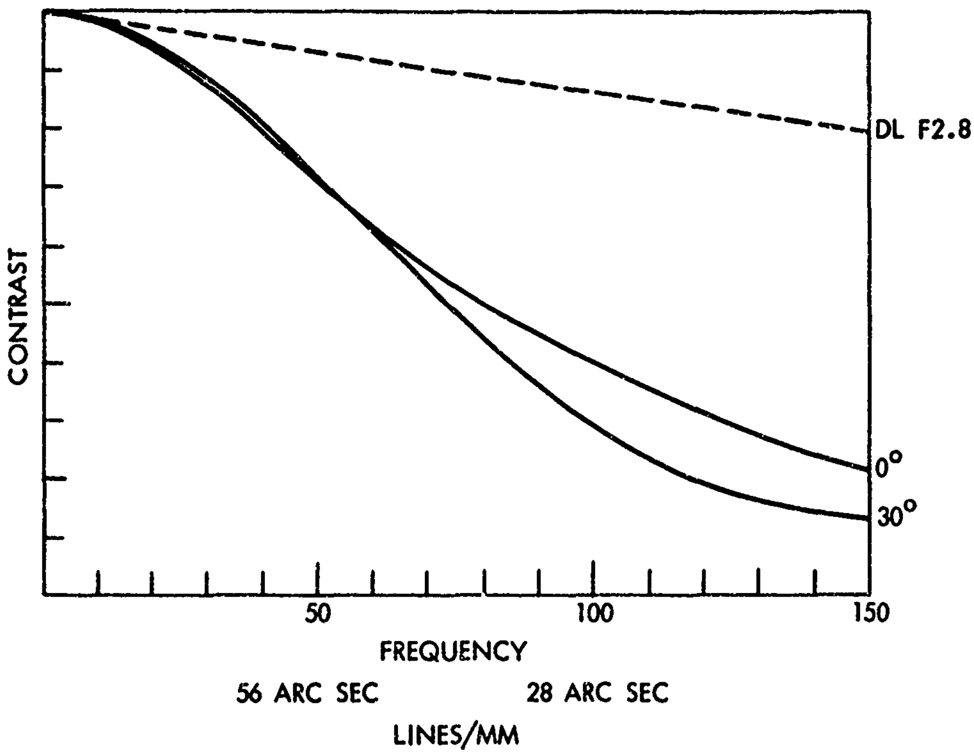


FIG. D-5 REPRESENTATIVE MODULATION TRANSFER FUNCTIONS (AXIAL)

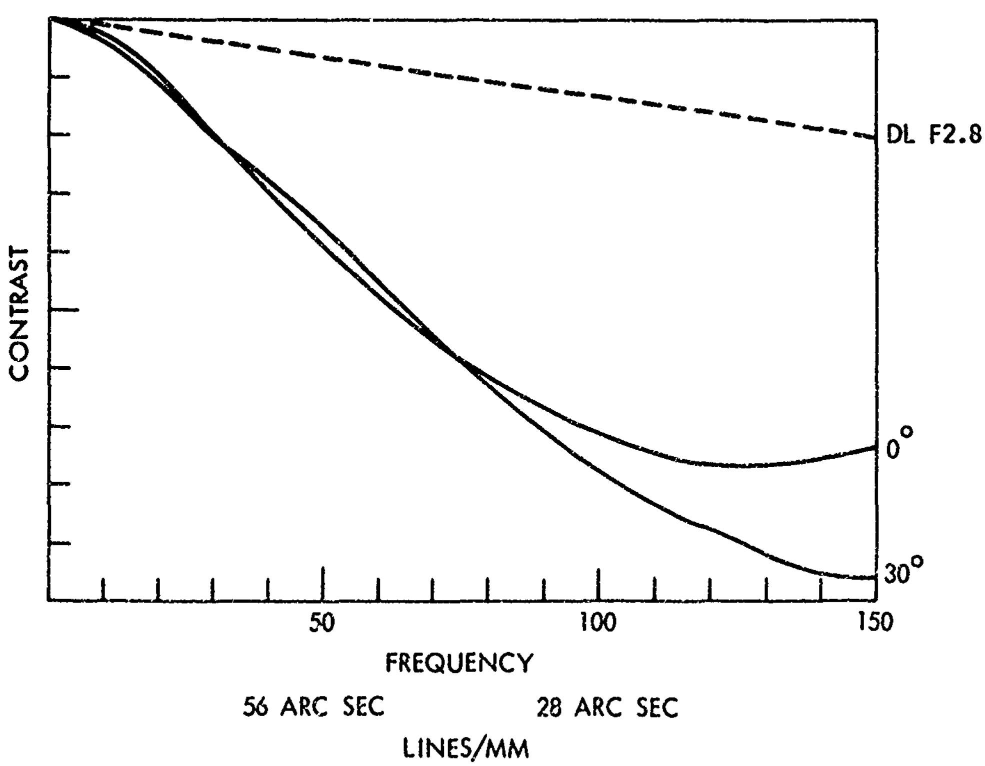


FIG. D-6 REPRESENTATIVE MODULATION TRANSFER FUNCTIONS (10° OFF AXIS)

compares with about one minute estimated resolution on the lens from which Figure D-1 was made. Diffraction limit on the F2.8 lens is approximately

$$\text{Lines/mm} = \frac{1426}{\text{F No.}} = \frac{1426}{2.8} = 510 \text{ lines/mm.}$$

This gives a minimum circle of confusion on a 75mm lens of

$$\text{Arc tan } \frac{1/510}{75} = \text{Arc tan } \frac{1.96 \times 10^{-3}}{7.5 \times 10^{1}} = \text{Arc tan } 2.61 \times 10^{-5} = 0.0015\text{mm.}$$

Diffraction limits=approximately five seconds of arc.

The calculated circle of confusion for meridianal rays is seen from the spot diagram Figure D-4 to be about twice the diffraction limit. This would make the lens diffraction limited at about F.5.6, giving a maximum resolution of about 250 lines per millimeter. Using the usual formula for total system resolution:

$$1/R = 1/R_1 + 1/R_f \text{ or } R = \frac{R_f R_1}{R_f + R_1}$$

Gives: $$R = \frac{100 \times 250}{100 + 250} = \frac{2.5 \times 10^4}{3.5 \times 10^2} = 7.1 \times 10^1 \text{ or } 71 \text{ lines/mm}$$

as the maximum resolution for a system using 100 lines/mm film.

APPLICATION OF NON-SPHERICAL LENSES TO THE FULL-SPHERE PROBLEM. The non-spherical radial lens concept would seem to have several applications for strike photography. As a substitute for the panoramic type of camera it would appear to be capable of development into an instrument that would offer all of the recording quality presently available, plus the added advantages of a much less complex camera with fewer mechanical parts; smaller size for the same picture image size and less weight; and complete freedom from the rubber geometry and time-scanning distortion of the panoramic system. Obviously the optical elements would be more expensive to manufacture than those for a panoramic system. The relative merits and cost of the two systems should be determined in this field of use.

APPLICATIONS TO THE FULL-SPHERE PROBLEM. One technique has not been applied to the strike recording problem. This is indexing as opposed to scanning. The non-spherical system is ideal for this purpose, although the technique could be used with other lenses. For indexing the camera is pivoted on an axis which runs parallel to the long image dimension. Successive pictures are then made after the camera has been rotated on this axis an amount corresponding approximately to the number of degrees covered by the narrow field angle of the camera.

For the 50° x 150° non-spherical system, indexing the camera slightly over 50° between successive pictures covers a field somewhat in excess of 150° x 150° with three frames. Because of the rectangular format of the object space covered, three rectangles embracing 50° at the

center of the field, will overlap at the ends of the field. By extending the indexing angle above 50° we would approach total coverage of 150° x 180° at the expense of small blind areas near the center of the adjacent areas of each frame. Two such indexing systems placed back-to-back and combined with a gunsight camera which would fill in the missing 30° cone forward of the aircraft would give almost total coverage of the entire airspace around the aircraft except for the direct rear 30° cone. The feasibility of indexing as applied to the Fuller lens design has been demonstrated by the developers. It has not been explored with respect to the full-sphere problem. It seems reasonable at this point to assume that the indexing type of camera could be brought to a frame speed of 4-6 frames per second. If this frame rate could be attained in a practical system, "total" object space coverage at an efficiency of about 80 percent could be achieved at the sampling rate of two per second. Efficiency as used here indicates the total percentage of the total 4π steradian object space that is covered by the system.

APPENDIX E

REFERENCES

(1) Naval Air Development Center Report AM-6930, "Evaluation of KB-19A Motion Picture Camera", (6/23/69) (U)
(2) Technical Manual: NAVAIR 10-10AC-116: Technical Manual, Service, Still Picture Camera KB-18A (9/30/68) (U)
(3) Private communication: Milton Laikin: Laikin Optical Corp. Marina Del Rey, Calif. Concerning the possibility of designing a +90° lens with axial focal length of 3-4 inches to cover 70mm film. Also see NADC Report No. AM-TM 1372 (Aero Mechanics Dept.) Results of Performance, Environmental and Acceptance Tests of the F/1.9 Ulta-Opticor 197° Ultra Wide Angle Lens.
(4) U. S. Patents Nos. 3,251,266 (5/17/66) and 3,361,512 (1/2/68) to D. L. Fuller for Wide Angle Objectives having Non-Spherical Surfaces.
(5) R. S. Longhurst: Geometrical and Physical Optics (John Wiley & Sons) 2nd Edition 1967, p 352
(6) Warren J. Smith: Modern Optical Engineering (McGraw Hill Book Co.) 1966, p 333
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